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Development of Textile Reinforced Composites for Aircraft Structures

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ABSTRACT

NASA has been a leader in development of composite materials for aircraft applications during the past 25 years. In the early 1980's NASA and others conducted research to improve damage tolerance of composite structures through the use of toughened resins but these resins were not cost-effective. The aircraft industry wanted affordable, robust structures that could withstand the rigors of flight service with minimal damage. The cost and damage tolerance barriers of conventional laminated composites led NASA to focus on new concepts in composites which would incorporate the automated manufacturing methods of the textiles industry and which would incorporate through-the-thickness reinforcements. The NASA Advanced Composites Technology (ACT) Program provided the resources to extensively investigate the application of textile processes to next generation aircraft wing and fuselage structures. This paper discusses advanced textile material forms that have been developed, innovative machine concepts and key technology advancements required for future application of textile reinforced composites in commercial transport aircraft. Multiaxial warp knitting, triaxial braiding and through-the-thickness stitching are the three textile processes that have surfaced as the most promising for further development.

Textile reinforced composite structural elements that have been developed in the NASA ACT Program are discussed. Included are braided fuselage frames and window-belt reinforcements, woven/stitched lower fuselage side panels, stitched multiaxial warp knit wing skins, and braided wing stiffeners. In addition, low-cost processing concepts such as resin transfer molding (RTM), resin film infusion (RFI), and vacuum-assisted resin transfer molding (VARTM) are discussed. Process modeling concepts to predict resin flow and cure in textile preforms are also discussed.

KEYWORDS: Textile Reinforced Composites, Braiding, Knitting, Stitching, Resin Transfer Molding, Process Modeling

1.0 INTRODUCTION

NASA initiated a research program in the early 1980's to exploit the potential of textile reinforced composites as a cost-effective method of producing damage-tolerant primary aircraft structures [1]. Several textile material forms, including 2-D and 3-D weaving and braiding, multiaxial warp knitting, and through-the-thickness stitching were evaluated. Structural performance, fabricability, scale-up potential, and manufacturing cost were the primary focus of this research. Some of the potential benefits of textile reinforced composites are as follows: reduced material and assembly labor costs through automated fabrication of multilayer multidirectional preforms; reduced machining and material scrap through use of near net shape preforms; elimination of cold storage requirements and limits on shelf life for prepreg; reduced tooling costs for vacuum-assisted resin transfer molding compared to conventional autoclave processes; and improved damage tolerance and out-of-plane strength as a result of through-the-thickness stitching.

In the late 1980's NASA researchers were looking to develop breakthrough technologies that would significantly change the way composite structures were being built. The NASA Advanced Composites Technology (ACT) program [2], provided the impetus and resources to pursue these goals. Working with aircraft manufacturers, universities, and specialty textile fabricators, NASA began to develop a preliminary design database on available material forms and to focus research on key technology issues. At that point in time, textile reinforced composites moved from being a laboratory curiosity to large scale aircraft hardware development. Initial emphasis was on mechanical properties and structural performance, but the need for cost-effective fabrication concepts kept surfacing as the key technology need. With the new focus on affordability, NASA awarded several contracts to industry to begin development of new tooling concepts that could produce aircraft-quality textile reinforced composite structures[3]. Resin injection methods such as resin transfer molding(RTM), resin film infusion (RFI), and vacuum-assisted resin transfer molding (VARTM) would be the keys to successful fabrication of composite structures from dry textile preforms.

This paper summarizes the development of advanced material forms, textile machine advancements, analytical process models, fabrication of aircraft structural components, and lessons learned working with various textile material forms, machines and processes.

2.0 TEXTILE MATERIAL FORMS AND STRUCTURAL ELEMENTS

As preliminary design databases were generated, NASA and the U.S. aircraft manufacturers began to focus on the textile processes that offered the most promise. The textile processes listed in figure 1 were evaluated. The advantages and limitations of each process were established and decisions on further development were made. The textile material forms shown in figure 2 have shown the most promise for application to aircraft structures. Multiaxial warp knitting is a highly tailorable automated process that produces multidirectional broadgoods for large area coverage. Two-dimensional and three-dimensional braids are used to create stiffeners, frames and beams with complex cross-sections. Through-the-thickness stitching is an effective way to debulk preforms and to achieve improved out-of-plane strength and damage tolerance of composite structures.

The structural elements shown in figure 3 were selected by NASA and the aircraft manufacturers to demonstrate the applicability of textiles to fuselage structures. The combination of weaving and stitching was used to fabricate lower fuselage side panel preforms[4]. The fuselage panel shown in figure 4 has four circumferential frames and four longitudinal stiffeners. The intersections of the woven stiffeners and frames have continuous fibers through the intersection to provide structural continuity. The flanges of the woven frames are stitched to the woven skin material. Braided frames were used to fabricate curved fuselage keel panels [5], a typical panel is shown in figure 5. The fuselage parts were fabricated with either matched metal heated RTM tooling or RFI autoclave processes.

Because of the high load intensity and the propensity for foreign object damage, NASA focused most of its textiles research on damage tolerant wing structures, figure 6. Since most of the wing weight is in the upper and lower cover panels of the wing, they are a logical choice for pursuit of cost and weight savings. Some of the global design considerations for wing panels include strength, stiffness, and damage tolerance. Based on tests conducted previously by NASA and Boeing (formerly McDonnell Douglas), through-the-thickness stitching was chosen for the wing cover panels because a 100-percent improvement in compression-after-impact strength compared to laminated tape composites could be achieved [6].

Blade stiffeners and integral spar caps were chosen by Boeing as stiffening elements for the upper and lower wing cover panels. The upper cover skin stiffeners and spar caps are fabricated with Saertex multiaxial warp knit fabric. However, due to the curvature of the lower wing cover panel, contoured triaxially braided stiffeners were selected. The stiffeners and spar caps were stitched onto the wing skins to form integral wing cover panels with no mechanical fasteners.

Before proceeding to design and fabrication of a full-scale wing box, Boeing fabricated a 2.4 m by 3.7 m stub box with the stitched/RFI process as shown in figure 7. An interior view of a stub box cover panel is shown in figure 8. This box was stitched with a computer controlled heavy duty single needle machine similar to those used in the quilting industry. The stub box was successfully tested at NASA Langley and met the design requirements set forth by Boeing for commercial transport wing structures.

3.0 ADVANCED TEXTILE MACHINE DEVELOPMENT

The development of a high speed multi-needle stitching machine and improvements in the multiaxial warp knitting process were required to achieve affordable full-scale wing structures. The stitching machine had to be capable of stitching cover panel preforms that were 3.0 m wide by 15.2 m long by 38.1 mm thick at speeds up to 800 stitches per minute. The multiaxial warp knitting machine had to be capable of producing 2.5 m wide carbon fabric with an areal weight of 1425 g/m^2. The advanced stitching machine shown in figure 9 was developed by Ingersoll Milling Machine Company to meet the requirements of a full-scale wing box [7]. The high speed stitching heads were developed by Pathe Industries, Inc. The lower cover preform for the full-scale wing box is shown on the stitching machine bed in figure 9.

Multiaxial warp knitting is a highly automated process for producing multilayer broadgoods. Compared to woven broadgoods, the knitted fabrics have less crimp since the individual tows are not interlaced. Early machine concepts lacked proper tension control to maintain fiber alignment. Saertex and Liba teamed up to upgrade tension control mechanisms and to improve overall quality of carbon fabrics. A schematic of the Saertex/Liba machine is shown in figure 10. This machine can produce 5-ply carbon fabrics in one pass through the machine. A two-step process is required to produce a 7-ply fabric for the Boeing full-scale wing cover panels. Splicing concepts have been developed to produce fabrics up to 2.5 m wide.

4.0 FABRICATION OF TEXTILE REINFORCED COMPOSITES

Three resin transfer processes are commonly used to produce composites from dry textile preforms: (1) resin transfer molding (RTM), (2) resin film infusion (RFI), and (3) vacuum assisted resin transfer molding (VARTM). RTM is a good process to achieve high fiber volume fraction for complex shapes such as the curved fuselage frames shown in figure 5. RTM requires the use of expensive matched metal heated tools, such as Invar, and high pressure to pump liquid resin into net shape tools. High quality parts can be achieved but the cost is prohibitive for large parts such as wing skins.

RFI is a process being pursed by NASA and The Boeing Company to develop cost-effective wing structures for commercial transport aircraft [8]. The RFI process developed by Boeing consists of an outer mold line tool, an epoxy resin film, a near net shape textile preform, an inner mold line tool and a reusable vacuum bag. Resin slabs are placed on the outer mold line tool and the preform and inner mold line tools are placed on top of the resin. The entire assembly is covered with a reusable vacuum bag and the part is placed inside an autoclave. After the resin is melted, vacuum pressure is used to infuse resin into the preform. Once infiltrated, the part is cured under pressure and temperature in an autoclave. The keys to producing aircraft quality parts with the RFI process are understanding the compaction and permeability characteristics of the preform and understanding kinetics and viscosity profiles for the resin as a function of temperature. Figure 11 shows a full-scale 13m long stitched/RFI wing cover panel fabricated by Boeing under contract to NASA. The one-piece reusable vacuum bag used to cure the cover panel is shown in figure 12.

VARTM processes have been used for many years to fabricate fiberglass reinforced composite structures. The U.S. Naval Surface Warfare Center in Bethesda, MD has been the major promoter of this technology for composite marine applications [9]. The major advantages of VARTM processes compared to conventional autoclave processes are the lower cost of tooling, reduced cost of energy to cure composite parts, and almost unlimited part size(i.e., no size constraints based on the size of the autoclave). Until recently, VARTM was primarily used to fabricate glass reinforced polyester and vinyl ester composites. However, due to recent developments in resin and preform technologies, aircraft manufacturers are beginning to show significant interest in VARTM processes for graphite-epoxy and graphite-bismaleimide composite systems. One drawback to VARTM processes has been low fiber volume fraction compared to the higher fractions achievable with autoclave pressure. However, stitching and debulking methods have been developed to achieve preforms that are near net shape with little or no further compaction required during processing.

NASA has conducted contractual research with Seemann Composites, Inc. to establish the feasibility of their VARTM process to produce aircraft quality composite structures. Their proprietary process, called SCRIMP (Seemann Composites Resin Injection Molding Process) utilizes a resin distribution media to achieve full wet-out of the preform, figure 13. In addition, Seemann has developed a reusable bagging concept that eliminates most of the costs associated with conventional bagging procedures. Seemann Composites has also demonstrated SCRIMP for lightly-loaded general aviation aircraft structures. Figure 14 shows the one-sided tooling concept and the graphite preform for a small aircraft fuselage section and figure 15 shows the completed graphite/epoxy part after resin injection and cure. Current and future tooling developments for integral heating will eliminate the need for oven cure and postcure of composite parts fabricated with VARTM processes.

NASA is also investigating the feasibility of SCRIMP to produce aircraft quality heavily-loaded primary structures. Additional technology development is required to achieve dimensional control and acceptable fiber volume fractions for thick structural elements. Innovative tooling concepts will be required to meet typical assembly tolerances for aircraft structures. Stitching will be required to achieve near net shape prior to resin injection. The reusable bagging concept for a three stringer panel representative of wing structure is shown in figure 16. The ease of removing this bag from the stiffened panel is illustrated in figure 17, and the finished panel (after resin injection and cure) is shown in figure 18.

To eliminate trial and error processes, analytical models are required to predict resin flow into textile preforms. The models must be verified through precise experiments to demonstrate the modeling accuracy. Three-dimensional models are required to capture response adequately for complex preforms such as wing cover panels that contain stitched/knitted fabric skins and stitched/braided stiffeners. The objectives of the analytical model are to predict flow front position, resin viscosity and degree of cure as a function of temperature and time. A 3-D RFI process simulation model is under development by Virginia Polytechnic Institute and State University [10]. The RFI simulation includes resin flow, heat transfer, and thermochemical elements. A schematic of the 3-D finite element model for infusion of a stitched blade stiffener is shown in Figure 19. Experiments are currently being conducted to verify accuracy of the 3-D finite element model. For a two-stringer stitched panel, the predicted temperature distribution was within 6-percent of measured temperature and the predicted resin wet-out times were within 4 to 12-percent of measured times.

5.0 LESSONS LEARNED FROM TEXTILE DEVELOPMENT

Early attempts to develop complex equipment to fabricate near net shape multidirectional multilayer fabrics were unsuccessful. This result was primarily caused by the fact that various textile technologies were being stretched beyond their technical boundaries. Two- and three-dimensional braiding showed a lot of potential but available machine capacity limited the architecture and the size of the preforms that could be achieved. Folding or postforming of triaxial braided preforms offered the most flexibility in achieving small cross-section complex shapes. Multiaxial warp knitting proved to be the best process for large area multiaxial multilayer broadgoods but structural shapes had to be achieved through postforming and stitching. Through-the-thickness stitching proved to be the best textile process to achieve improved damage tolerance. Compared to processing with glass fibers, all textile machines investigated had to be slowed considerably when carbon fibers were used. Lessons learned to-date indicate that no one machine can produce the desired fiber architectures for all complex shape aircraft structural preforms. In addition, more stringent in-process controls and inspection techniques are needed to minimize scrap and to reduce costs. Invariably, processing defects and handling damage will occur. Since scrap of large expensive parts is not an option, repair concepts must be developed. Methods to reinfuse resin starved areas must be developed and repair concepts to restore damaged structure to original strength must also be developed.

Analytical models are required to eliminate costly trial and error processes that are frequently used in tool design and development of processing cycles. Resin viscosity and cure kinetics must be characterized to consistently achieve high quality composite parts. Since compaction and permeability behavior are different for each fiber architecture and preform configuration, empirical relationships must be developed for input to analytical models.

Tooling concepts that can accommodate variability in dry preform bulk and permeability must be developed to achieve uniform resin flow and fiber wet-out. Dimensional tolerances on tooling is critical to avoid racetracking or short circuiting of resin during the infusion process. Further development of compaction methods and soft tooling concepts such as VARTM will lead to reduced scrap and lower manufacturing costs.

6.0 CONCLUDING REMARKS

Major advancements in the development of textile preforms in concert with resin transfer tooling concepts makes it feasible to fabricate high quality damage tolerant aircraft structures with these material forms and processes. Recent developments in improved tension control of tows in the multiaxial warp knitting process have made this the material of choice for large area multidirectional broadgoods. Innovative tooling concepts have been developed to produce curved braided preforms for application to fuselage frames and wing stiffeners for commercial transport aircraft. NASA and Boeing have demonstrated that through-the-thickness stitching of dry textile preforms can provide a 100-percent increase in damage tolerance of composite wing structures compared to laminated tape construction techniques.

Recent investments in a second generation stitching machine with multiple heads are expected to pay-off in terms of improved quality, higher speed, and lower cost. Low cost resin transfer molding processes are now being applied to fabrication of aircraft quality, heavily-loaded primary structures. Modeling studies of resin transfer molding will focus on prediction of resin flow into complex textile preforms to insure high quality, high speed fabrication at lower costs. Additional development of out-of-autoclave vacuum-assisted resin transfer molding (VARTM) processes could lead to significantly lower tooling and fabrication costs for large area composite structures.

7.0 REFERENCES

1. Dexter, H. B.; Camponeschi, E. T. and Peebles, L., ed., "Proceedings of Working Group Meeting on 3-D Composite Materials", NASA CP 2420, 1986.

2. Dexter, H. B. and Stein, B. A.: "Advanced Composite Materials for Airframe Structures", Fiber-TEX 1987- First Conference on Advanced Engineering Fibers and Textile Structures for Composites, NASA CP 3001, Part 1, 1988, pp. 1-29.

3. Davis, J. G., Jr. and Bohon, H. L., ed.: "First NASA Advanced Composites Technology Conference", NASA CP 3104 , Part 1, 1991.

4. Suarez, J. A. and Buttitta, C., et al.: "Novel Composites for Wing and Fuselage Applications- *Textile Reinforced Composites and Design Guidelines",* NASA Contractor Report 201612, September 1996.

5. Jackson, A. C.; Barrie, R. C. and Chu, R.L.: "Textile Composite Fuselage Development", Proceedings of the Third NASA ACT Conference, NASA CP 3178, Vol 1, Part 1, 1992, pp. 79-96.

6. Hawley, A. V.: "Detail Design Development of a Transport Aircraft Composite Wing", Proceedings of the Sixth NASA/DoD ACT Conference, NASA CP 3326, Vol 1, Part 1, 1996, pp. 131-154.

7. Thrash, P. J., and Miller, J. I.: "Design of a Stitching Machine for Transport Aircraft Composite Wings", Proceedings of the Sixth NASA/DoD ACT Conference, NASA CP 3326, Vol 1, Part 1, 1996, pp. 191-208.

8. Markus, A. M.: "Resin Transfer Molding for Composite Primary Wing and Fuselage Structures", Proceedings of the Ninth DoD/NASA/FAA Conference on Fibrous Composites in Structural Design, NASA CP 3154, 1992, pp. 141-167.

9. Critchfield. M.O., et al, "Low-Cost Fabrication of Composite Ship Structures Using Vacuum-Assisted Resin Transfer Molding", Proceedings of the Composites in Marine Applications Symposium, November, 1992, Seattle, WA.

10. Loos, A. C., et al, "Resin Film Infusion(RFI) Process Simulation of Complex Wing Structures", Proceedings of the Fifth NASA/DoD Advanced Composites Technology Conference, NASA CP 3294, Vol 1, Part 2, 1995, pp. 811-833.

Textile Process	Advantages	Limitations
Low Crimp Uniweave	High in-plane properties Good tailorability Highly automated preform fabrication process	Low transverse and out-of-plane properties Poor fabric stability Labor intensive ply lay-up
2-D Woven Fabric	Good in-plane properties Good drapability Highly automated preform Fabrication process Integrally woven shapes possible Suited for large area coverage Extensive data base	Limited tailorability for off-axis properties Low out-of-plane properties
3-D Woven Fabric	Moderate in-plane and out-of-plane properties Automated preform fabrication process Limited woven shapes possible	Limited tailorability for off-axis properties Poor drapability
2-D Braided Preform	Good balance in off-axis properties Automated preform fabrication process Well suited for complex curved shapes Good drapability	Size limitation due to machine availability Low out-of-plane properties
3-D Braided Preform	Good balance in in-plane and out-of-plane properties Well suited for complex shapes	Slow preform fabrication process Size limitation due to machine availability
Multiaxial Warp Knit	Good tailorability for balanced in-plane properties Highly automated preform fabrication process Multi-layer high throughput material suited for large area coverage	Low out-of-plane properties
Stitching	Good in-plane properties Highly automated process provides excellent damage tolerance and out-of-plane strength Excellent assembly aid	Small reduction in in-plane properties Poor accessibility to complex curved shapes

Figure 1. Application potential of textile reinforced composite materials for aircraft structures.

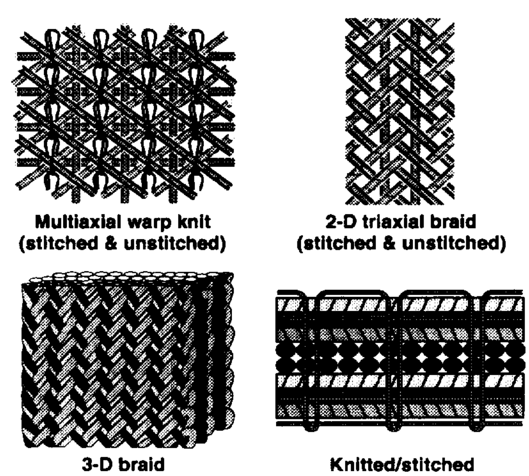

Figure 2. Textile material forms.

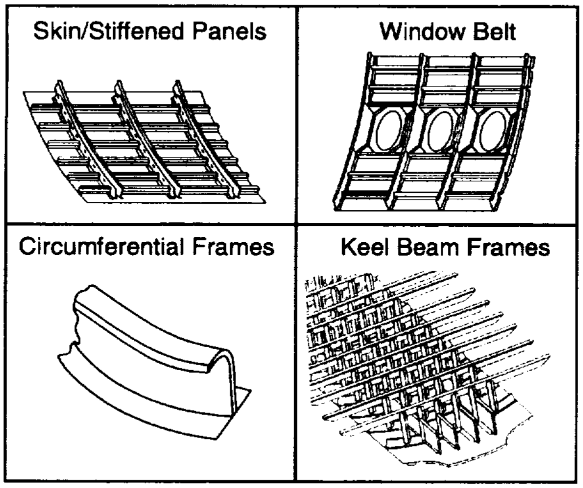

Figure 3. Application of textile reinforced composites in fuselage structures.

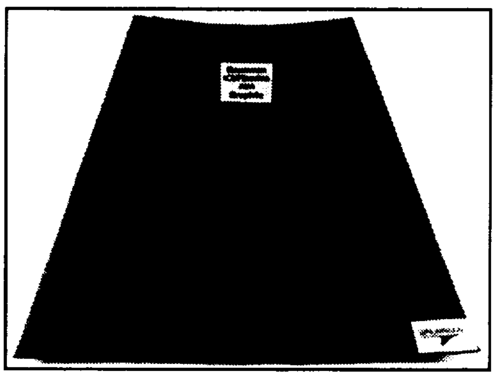

Figure 4. Woven/stitched lower fuselage side panel preform.

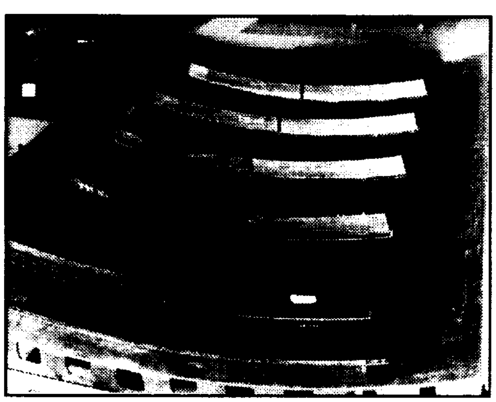

Figure 5. Curved braided frames for fuselage keel structure.

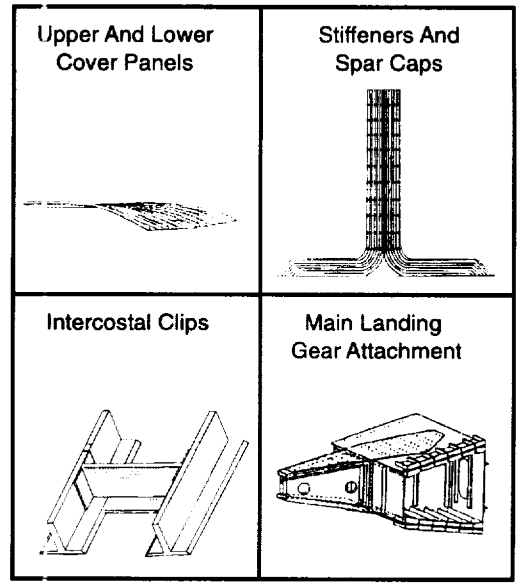

Figure 6. Application of textile reinforced composites in wing structures.

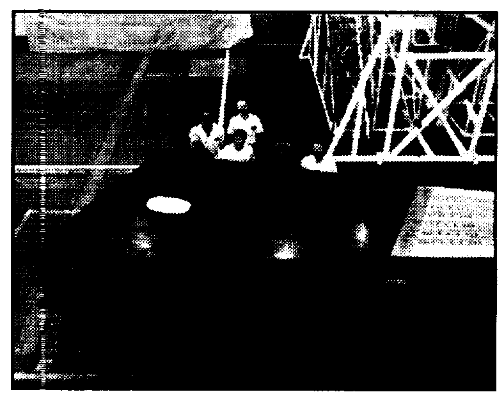

Figure 7. Stitched/resin film infused wing stub box.

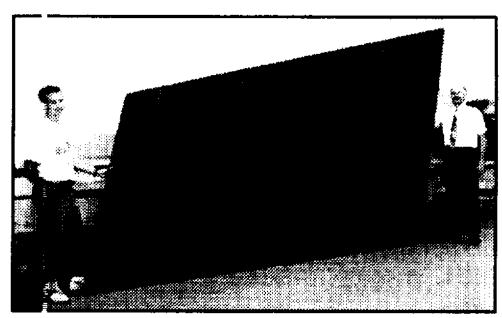

Figure 8. Interior view of stub box cover panel.

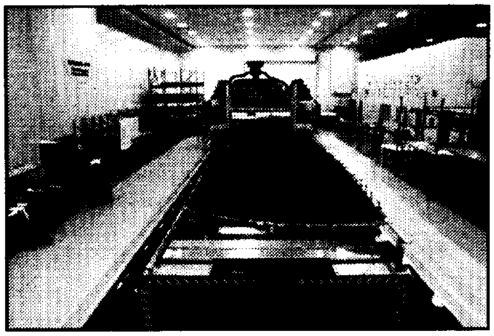

Figure 9. Advanced stitching machine for wing cover panels.

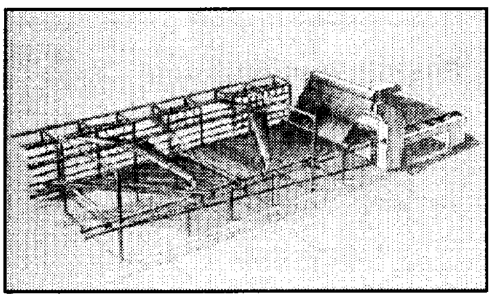

Figure 10. Schematic of Saertex/Liba multiaxial warp knitting machine.

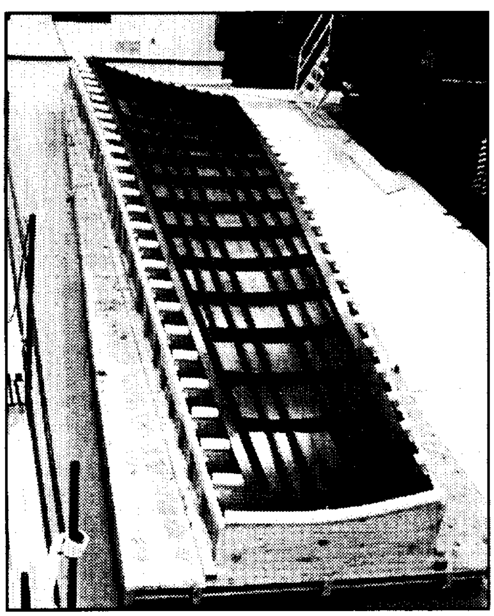

Figure 11. Stitched/Resin film infused composite wing cover panel.

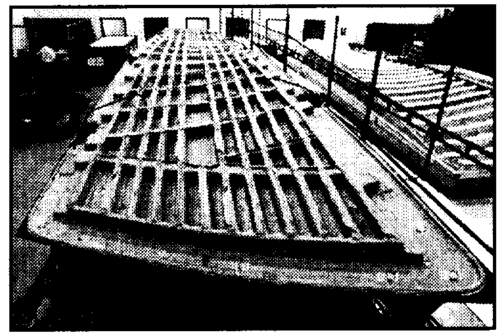

Figure 12. Reusable vacuum bag for wing cover panel.

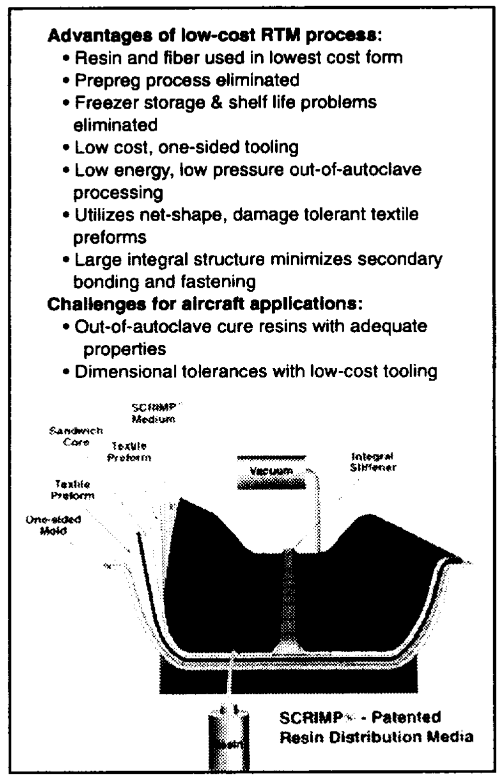

Figure 13. Low-cost vacuum-assisted resin transfer molding process.

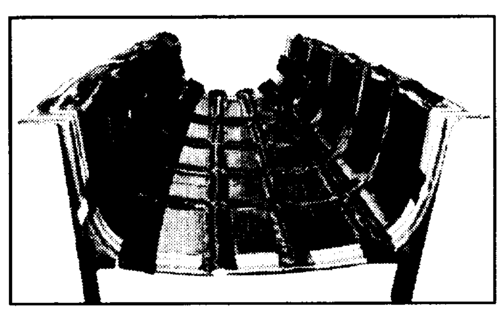

Figure 14. Vacuum-assisted resin transfer molding tooling for fuselage section.

Figure 15. Vacuum-assisted resin transfer molded fuselage section.

Figure 16. Reusable vacuum bag for VARTM of 3-stringer panel.

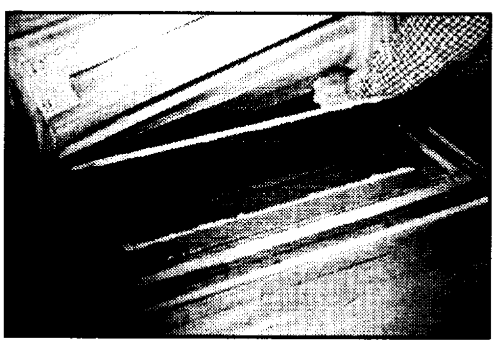

Figure 17. Removal of reusable vacuum bag from VARTM stiffened panel.

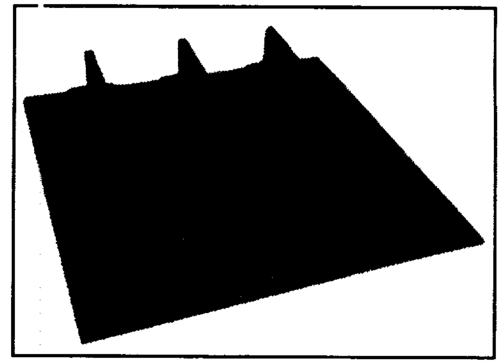

Figure 18. Stiffened panel fabricated by VARTM.

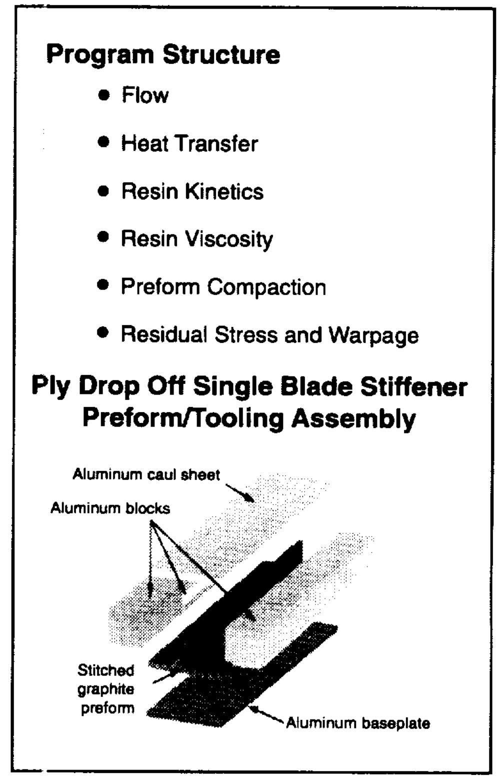

Figure 19. Three-dimensional resin film fusion model.